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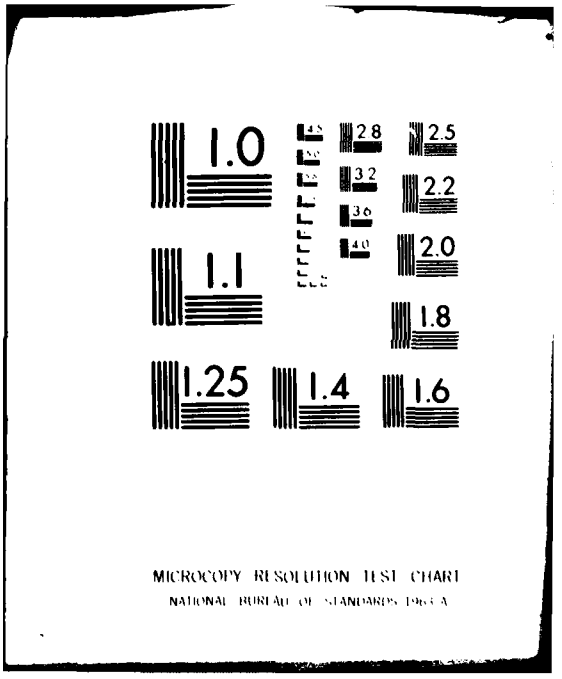
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NWC Technical Memorandum 3634

THE ADAPTATION OF COLOR TO INDUSTRIAL RADIOGRAPHY

(A Feasibility Study)

Prepared by

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Range Department

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It has been known for some time that certain chemicals luminesce when impinged by X- or gamma rays. The specific color and brightness of the luminescence thus produced is known to be a function of the chemical itself, the wavelength of the impinging rays, and the flux density of the impinging rays. Because of the inherent problems associated with reading conventional X-rays, it would be of great value to take advantage of the color luminescence phenomenon in producing the film images to be read during structural assessment. This memorandum is disseminated to report on the current state-of-the-art in producing color X-ray images.

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FOREWORD

Conventional industrial radiography utilizes black and white film as the medium for permanently recording images produced by the interaction of X-rays with the material they traverse.

This document is issued to report on a state-of-the-art study of the feasibility of introducing color techniques into industrial radiography.

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INTRODUCTION

It has been known for some time that certain chemicals luminesce when impinged by X- or gamma rays. The specific color and brightness of the luminescence thus produced is known to be a function of the chemical itself, the wavelength of the impinging rays, and the flux density of the impinging rays.

Because of the inherent problems associated with reading conventional X-rays, it would be great value to take advantage of the color luminescence phenomenon in producing the film images to be read during structural assessment. This memorandum is disseminated to report on the current state-of-the-art in producing color X-ray images.

PHOTO FLUORESCENCE

The existence of the X-rays was discovered by Roentgen when a paper screen covered with crystals of platinum-barium cyanide was seen to fluoresce when exposed to a highly evacuated tube through which he was passing an electronic discharge. This phenomenon of a material being capable of absorbing the invisible X-radiation and then to re-radiate that energy or a portion thereof at a longer wavelength visible to the human eye constitutes the basis for all modern day radiography.

The fluoroscope is the most analogous application, however, in both medical and industrial radiography the use of intensifying screens is a direct application of the fluorescence phenomenon.

THE INTERACTION OF X-RAY WITH MATTER

A quantum of X-rays impinging on the surface of a material will react with the material as it traverses the material thickness. That quantum of X-rays exiting the back surface of the material will not be of the same quality or quantity as it was originally. While some of the

impinging X-rays will traverse through the material with no interaction, some will be absorbed and some will scatter within the material.

X-rays are absorbed by some materials much more than by others. The amount of X-ray photons absorbed, resulting in the decrease of a given X-ray intensity, is a function of the thickness and density of the material traversed and the atomic number of that material.

Those scattered X-ray photons are in effect those which exit the material through which they have just traversed in any other than the same direction of impingment. Thus, scattered X-ray photons may or may not undergo an energy change.

The three processes which result in a total decrease in X-ray photon flux as it travels through a material are termed the "photoelectric effect", "pair production" and "Compton scattering". These processes are illustrated in Figures 1, 2, and 3. In the photoelectric effect, the X-ray photon is absorbed by an atom and one of the bound electrons in the atom is ejected. The impinging X-ray photon imparts all of its energy to the orbital electron, predominantly in the K and L shells of the atom and is thus absorbed. Due to the resultant increase in kinetic energy of the orbital electron, it overcomes the attractive force of its atom's nucleus and flies from its orbit. The high velocity electron, now called a "photo electron" has sufficient energy to penetrate the electron cloud of other atoms and knock outer electrons from their orbits, thus causing secondary "ion pairs". This process continues until the photo electron's energy is expended. Generally the photoelectric effect is predominant for X-ray photons at the lower energy levels (below 70 KeV). The probability of this process occurring increases with increasing atomic number of the absorbing material and decreases as the X-ray photon energy increases.

The pair production - absorption - process occurs only with high-energy X-ray photons (above 1 MeV). In this process, the incoming X-ray photon has sufficient energy to penetrate the electron cloud surrounding the atom's nucleus imparting all of its energy. This energy, thus imparted to the atom causes two electrons, one positive (positron) and one

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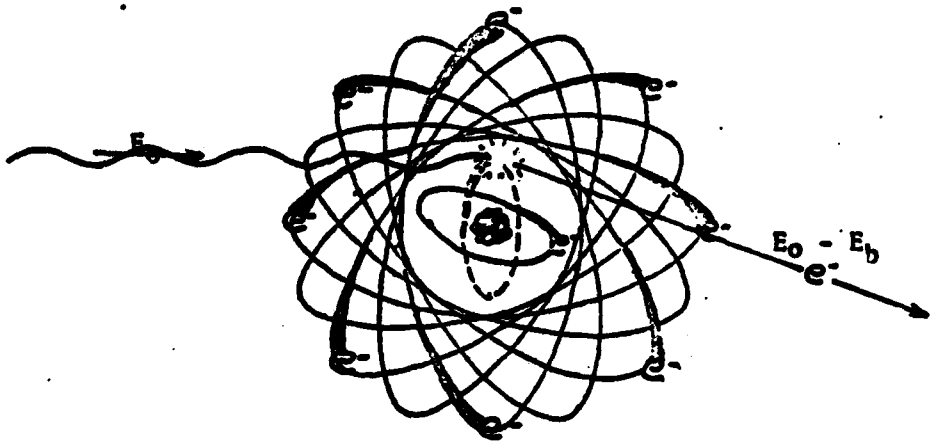
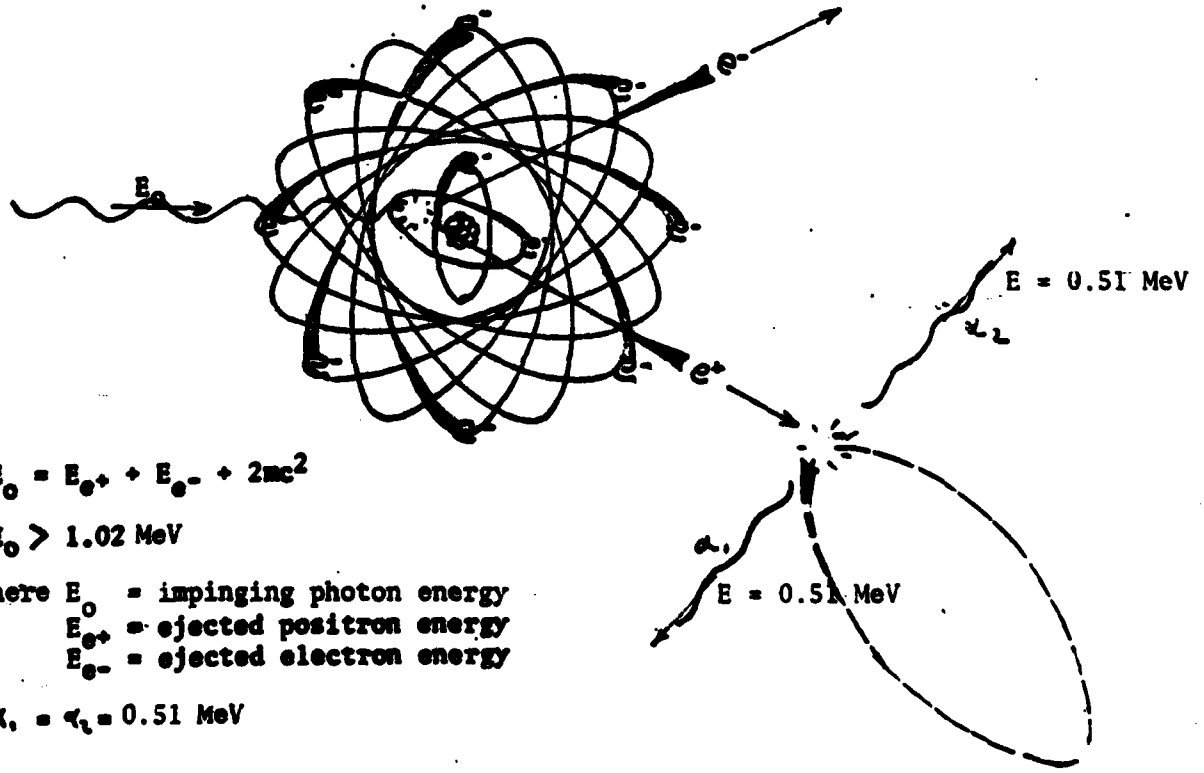


$$E_e = E_o - E_b$$

Where E_e = energy of ejected electron
E_o = impinging photon energy
E_b = electron binding energy

FIGURE 1. Photoelectric effect.



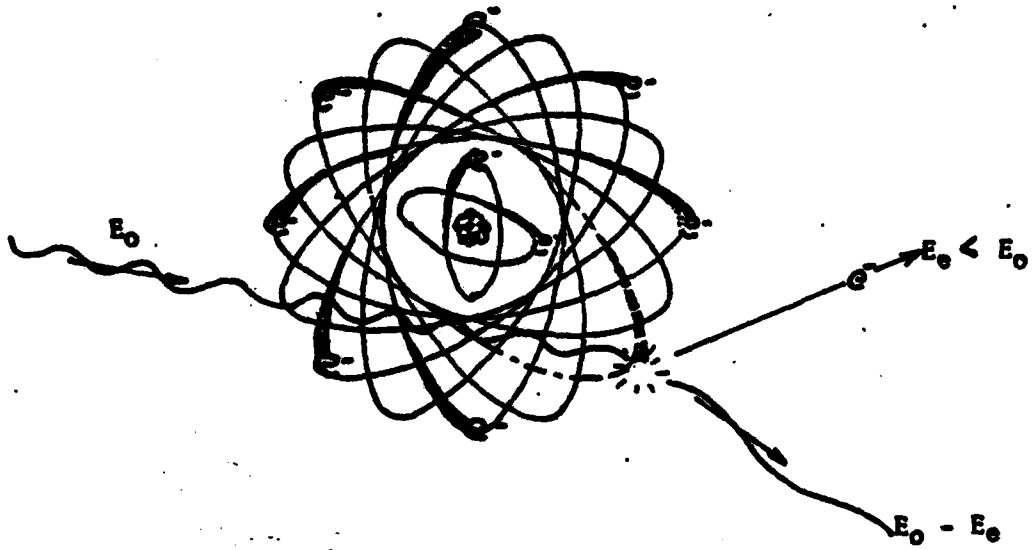
$$E_o = E_{e+} + E_{e-} + 2mc^2$$

$$E_o > 1.02 \text{ MeV}$$

Where E_o = impinging photon energy
E_{e+} = ejected positron energy
E_{e-} = ejected electron energy

$\alpha_1 = \alpha_2 = 0.51$ MeV

FIGURE 2. Pair production.



$$E_p = E_o - E_e$$

Where E_e = energy of ejected electron
E_o = impinging photon energy
E_p = energy of scattered photon

FIGURE 3. Compton scattering effect.

negative in charge, to be released from the electron shell. The negative electron reacts as above until all of its energy is expended. The positron reacts similarly causing secondary ionization while it is in motion, but when the greater part of its energy is expended it collides with a free electron converting the mass of each into pure energy. Thus, two gamma rays of 0.51 MeV each are produced. The two gamma rays so produced are absorbed by the photoelectric process above or scattered by the Compton scattering effect. The probability of pair production increases as the X-ray photon energy increases and as the atomic number of the atoms of the absorbing material increases.

The Compton scattering process occurs when an X-ray photon interacts with an orbital electron on an atom in an absorbing material, but differs from the photoelectric effect in that the X-ray photon gives up only a portion of its energy and is deflected from its original path in a weakened condition. The deflected photon will continue to travel through the absorbing material until it again undergoes scattering, or is absorbed through the photoelectric effect or exits the surface of the material. The high-velocity electron ejected from the atom impinged by the X-ray photon produces secondary ionization in the same manner as the photoelectron.

In the Compton scattering process, the energy of the reflected X-ray photon is a function of the absorbing material and does not change appreciably with the change in the impinging X-ray photon energy as long as the impinging photon is of sufficient energy to interact.

SCINTILLATION

The three processes so far described can all result in the ejection of a free electron. The mechanism for the production of scintillation is thus established. Since inorganic materials, being relatively denser and, generally speaking, having a high atomic number, are the better absorbers of X-ray photons, it follows that they would also be desirable as a scintillating medium.

Inorganic scintillating materials are crystals of inorganic salts, primarily the alkali halides containing small amounts of impurities as activators for the luminescence process. The mechanism for the production of luminescence can be described in terms of the "band picture of solids".

A pure alkali halide crystal is presented in the band theory by a valence band of energies which is normally completely filled with electrons and by a conduction band of energies which is normally empty. The conduction band is separated from the filled valence band by a forbidden

band of energies. Electrons cannot exist in the forbidden band. However, imperfections in the crystal such as impurity atoms or lattice valences can create energy levels in the forbidden band at random and isolated points within the crystal. Figure 4 depicts a schematic of the energy levels in an alkali-halide crystal.

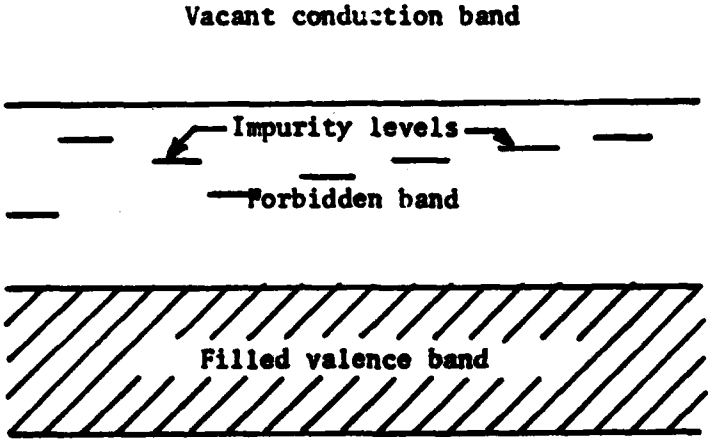


FIGURE 4. Band picture of solids.

The passage of an X-ray photon through the crystal can release electrons from the valence band to the conduction band, thus creating an electron in an excited state. This excited electron in the conduction band can wander through the crystal until it comes to the vicinity of an imperfection in the crystal, where it can drop to the energy level associated with the imperfection and immediately back to the valence band. The energy of excitation is thus given up and may be released as radiation at a longer wavelength. This released energy is frequently in the visible or ultraviolet range or it may be released as heat within the crystal.

Many substances show the properties of emitting visible light when subjected to a beam of X-ray photons. The term "fluorescence" or

"fluorescent emission" is used if the resultant time between electron excitation and light emission is on the order of 10^{-8} seconds. Reactions taking longer, i.e., the electron does not return to the ground state immediately, are referred to as "phosphorescence". Phosphorescence is associated with decay time for fluorescent screens.

For X-ray photons with quantum energies roughly greater than 500 KeV and less than 3 MeV, the Compton scattering effect is the predominating process for nearly all scintillations. Thus, the scintillations produced are relatively independent of the direction of the primary photon beam responsible for their generation. However, the wavelength of the emission, the light yield, and the decay time are predictable. Table I depicts representative data for some of the more common inorganic scintillators.

Although the scintillation characteristics of the scintillator are relatively independent of X-ray photon energy in the energy range of 500 KeV to 3 MeV, the light yield and decay time are both a function of scintillator transparency to its own emissions and to the X-ray photon flux impinging the scintillator.

BRIGHTNESS LEVEL OF SCINTILLATORS

The most formatable technical problem associated with scintillation techniques and fluoroscopic screen manufacturing is screen brightness. Visual acuity and intensity discrimination of the eye at the low brightness level is far lower than that with which a radiographer normally views radiographs on a standard illuminator.

The brightness level or the total illumination that any one type of fluorescent material produces is sometimes referred to as light yield; however, it remains to be predominantly a function of the energy and quantity of impinging X-rays. Each type of luminescent material will thus produce a maximum response to a given X-ray energy and quantity. For a given material the brightness will thus follow somewhat of a normal

TABLE I. Inorganic Scintillators.

Scintillator (activator in parentheses)	Density, gm/cm^3	Effective atomic number, $\bar{Z}r$	Wavelength of emission, Å	Refractive Index	Light yield (anthracene = 1.00	Decay time, μ sec
ZnS (Ag)	4.1	27	4500	2.4	(2.0)	(>1)
CdS (Ag)	4.8	44	7600	2.5	(2.0)	(>1)
NaI (Tl)	3.67	50	4100	1.7	2.0	0.25
KI (Tl)	3.13	49	4100	1.68	0.8	>1
NaCl (Ag)	2.17	16	2450, 3850	1.54	1.15	>1
LiI (Tl, Sn, or Eu)	4.06	52	Blue, green	1.95		
LiF (AgCl)		8.1		1.39	0.05	
CsI (Tl)	4.51	54	White	1.79	1.5	>1
CsBr (Tl)	4.44	49		1.70	2.0	>1
$CaWO_4$	6.06	59	4300	1.92	1.0	>1

bell-shaped distribution peaking out at some optimum photon energy, usually less than 100 KV.

Once the luminescence phenomenon has been established for a given material, the material itself will act as an absorber for the light produced, i.e., if the material is not transparent to the light it produces, the effective light output is, for all practical purposes, produced only by the surface atoms of the material. Thus, the total thickness of the material, the crystalline shape and spacing, as well as the crystal size itself become limiting factors in total brightness.

Optimum light yield for a given luminous material then can be best achieved by using a single crystal or a mosaic crystal machined to a minimum thickness. The type of crystal to be used would then depend on the X-ray energy and color of luminescence desired.

GEOMETRIC UNSHARPNESS

As has been previously pointed out, the light photons produced by the luminescence phenomenon are produced by the interactions of X-ray photons and the absorbing medium and are predominantly characterized by scatter. Any image thus produced will be lacking in sharpness. The divergence of the light photons from a point of generation within a crystal will tend to spread, both within and without the crystal, resulting in a "fuzzy" or poorly defined image.

The geometric unsharpness is thus also dependent on the fluorescing crystal size, spacing, and thickness. Optimum image sharpness or definition can be achieved only by using a single crystal or mosaic crystal machined to a very fine thickness.

LUMINESCENCE AND COLOR

As can be seen from Figure 5, the wavelength of emission is given for the selected inorganic scintillators. The wavelengths depicted in

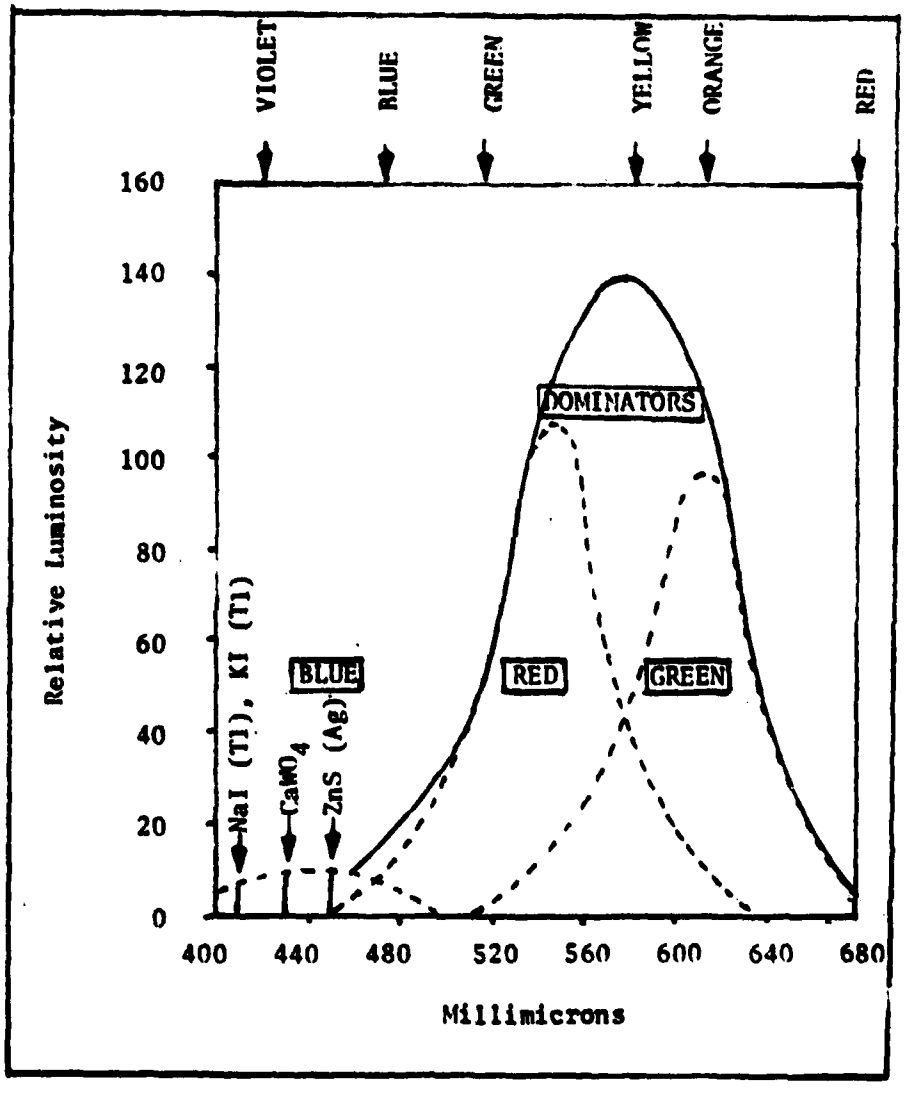


FIGURE 5. Fluorescent emissions and retinal color receptors for selected inorganic scintillators.

Figure 5 are overlayed on the color spectrum corresponding to the wavelength sensitivity of the eyes' retinal color receptors according to the Young-Helmholtz theory.

The wavelengths of emission depicted in Figure 5 are in reality themselves representative of a normal bell-shaped curve peaking at the indicated wavelength and for the most part and well into the violet color spectrum with a low relative luminesocity.

It has been discovered by manufacturers of fluorescopic screens that the color of fluorescent emissions can be controlled by introducing minute quantities of inorganic impurities in the crystal growth process. Zinc sulfide for example, can be made to fluoresce in the yellow-green color, well within the dominator region of the eye's sensitivity, by the addition of cadmium impurities in the fluorescent crystal's growth process. Figure 6 shows such a color emission shift for zinc sulfide. Other screen manufacturers commercially produce fluorescent screens whose dominant wavelength emissions fluoresce in other colors. However, commercially available fluorescent materials are produced to correspond to maximum wavelength sensitivity of the film being used to record the fluorescence.

FLUORESCENT SCREENS

Typically commercially produced fluorescent screens are made by coating a luminescent material onto a cardboard backing. The fabrication process typically consists of suspending small crystals of the luminescent material in an inert binder solution and then dipping the cardboard backing into the solution. Brushing or spraying is sometimes used to apply a coating of the crystal suspension onto one side of the cardboard only.

The resultant product as shown in cross-section in Figure 7 results in each crystal acting as an independent fluorescing medium. The inherent problems associated with this scheme of things are that:

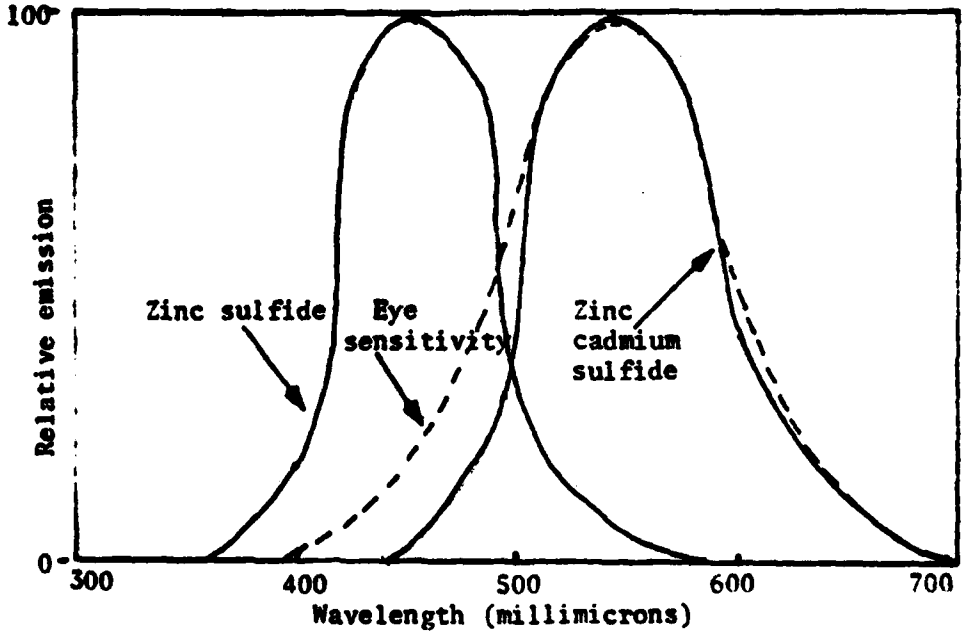


FIGURE 6. Color emission shift of zinc sulfide by the addition of cadmium impurities.

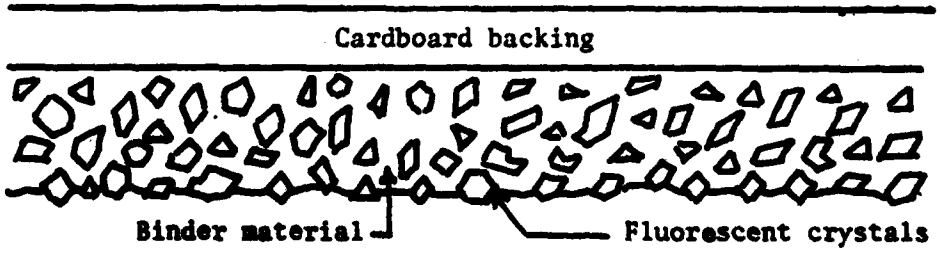


FIGURE 7. Cross-sectional view of fluorescent screen.

1. The quantity of impurities introduced in each crystal cannot be uniformly controlled.

2. The geometric spacing and orientation of each crystal in the binder cannot be controlled.

3. The "stacking" of individual crystals to give uniform thickness cannot be controlled.

4. The crystal variation in size and shape cannot be uniformly controlled.

Thus, an image produced will be lacking in both definition and sensitivity.

CONCLUSIONS

Generally speaking then, it can be concluded that conventional photo fluorescent screens result in the production of a poorer image quality than can normally be obtained with conventional X-ray inspection.

However, a single crystal of sufficient diameter machined to some minimum wafer thickness and mounted in, or onto, an optically clear support could dramatically improve both the definition and sensitivity of the image produced, by alleviating the inherent problems associated with the multicrystal screens.

Theoretically then, it is possible to produce a monocromatic image corresponding to the dominator region of eye sensitivity. The image thus produced, however, may have a low light yield requiring the use of photomultiplier tubes as "brighteners".

The problem remains, however, that the image produced will be monocromatic. Any attempt to produce a color spectrum will then require that a single film, if a film is to be used to record the image, be exposed incrementally using two or more fluorescent crystals. The overall effect of this technique would in effect, increase the radiation "dose" or exposure time required to produce the image.

Although current crystal technology severely limits the applicability of any direct approach to producing color X-ray images for the industrial radiographer, it should not be ruled out that a laboratory model might prove beneficial in a stereographic approach, or that a monocromatic image electronically enhanced would be preferable to the human eye in descerning shade variations.